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Performance of Add-On Type Heat Pump Water Heaters Using Two Different Test Methods

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NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

ABSTRACT

Two different makes of add-on (without tank) heat pump water heaters (HPWH) were tested. Each of the HPWH's was subjected to a series of recovery tests similar to the Department of Energy (DOE) recovery test for conventional electric water heaters. The results of the tests (recovery efficiency, standby loss, input power, storage tank capacity and energy used) were used to compute an energy factor which could be used to calculate the estimated annual operating cost of such HPWH's. The energy factor was also determined by a series of simulated use tests consisting of four equal draws totaling 64.3 gallons of hot water per day. The average energy factor derived from the recovery tes ts was about 13 percent higher than that derived from the simulated use tests. Based upon the results of this limited test program it was recommended that a simulated use test be used to determine the energy factor for HPWH's without tank.

Key words: appliances; energy; heat pump water heaters; test procedures; testing; water heaters

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NOMENCLATURE

Cc	Daily hot water energy consumption (Btu/day).
Cus	Average hourly hot water storage loss (Btu/hour).
Cwh	Daily water heating energy consumption (Btu/day).
Cy	Average daily energy consumption, derived from cold tank recovery test (kilowatt hours/day).
Er	Recovery efficiency (dimensionless).
Erd	Recovery efficiency during the differential temperature rise from thermostat cut-in to thermostat cut-out (dimensionless).
EF	Energy factor, the ratio of daily hot water energy consumption to the daily energy consumption with a particular water heater (dimensionless).
EFsu	Energy factor, derived from a 24 hour test with a hot tank and simulated daily use of 64.3 gallons of hot water (dimensionless).
k	Specific heat of water (8.25 Btu/(gallon, °F))
P	Power used by heat pump water heater (kilowatts)
R	Recovery rate (gallons/hour)
S	Standby loss, expressed as a decimal loss per hour (1/hour)
ΔT1	Difference between the initial mean tank temperature and the final mean tank temperature during a recovery test, (Tf, -Ti),(°F).
ΔT2	Difference between the average value of the mean tank temperature and the average value of the ambient air temperature during the standby loss test (°F).
ΔT3	Difference between the initial and final mean tank temperature from the start to the end of a standby loss test, ($T_f - T_i$), (°F).
ΔT4	The nominal difference between the initial mean tank temperature and the final mean tank temperature (90°F).
ΔT5	The difference between the nominal mean tank temperature and the nominal mean ambient air temperature (60°F).
ΔT6	Difference between the mean high and mean low tank water temperature with thermostat differential; $\left(T_{max,\ cut\ out} - T_{min,\ cut\ in}\right)$,(°F)
Ti	Mean tank temperature, initial, at the start of a test (°F).

Tf	Mean tank temperature, final, at the end of a test (°F).
Tr	Duration of the recovery test (hours).
Ts	Duration of the standby loss test (hours).
U	The nominal daily hot water usage (64.3 gallons).
V	Tank capacity (gallons).
Z	Total electrical energy to the heat pump during a particular test (kilowatt hours).

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1. INTRODUCTION

Currently there are no established Department of Energy (DOE) test procedures for heat pump water heaters (HPWH). There are test procedures proposed by Gas Appliance Manufacturers Association (GAMA) [1]* and American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) that use a recovery test from a 55°F** starting water temperature and a standby loss test similar to the published DOE test procedure for conventional electric water heaters [2] to calculate an energy factor. The GAMA and ASHRAE test procedures are proposed and are not presently approved.

In this study two different add-on HPWH's (without tank) were tested using the proposed ASHRAE / GAMA type of recovery test . The objective was to determine their operating characteristics based upon these test procedures. It was also an objective of this study to determine how the energy factors*** so determined would compare with energy factors determined by a simulated use test. The simulated use test consisted of four equal draws totaling 64.3 gallons**** of hot water per day. These latter tests were performed in order to simulate the HPWH installed in a home.

The test data from these different test procedures were collected and analyzed to determine the differences in daily water heater energy consumption as computed with the cold tank recovery test with that measured with a simulated day's HPWH use.

2. TEST PROCEDURE

2.1 TEST SETUP AND LABORATORY CONDITIONS

The test setup is shown in figure 1. For all tests, the supply water temperature was conditioned to 55°F as prescribed in the test procedures proposed by GAMA and ASHRAE. All tests were conducted in a laboratory 11.6 ft wide, 18.0 ft long, and 9.9 ft high with a resulting volume of 1879 cubic feet. There was a doorway 4.0 ft wide and 7.2 ft high with a resulting area of 28.8 square feet. This doorway remained open for all tests. The ambient temperature ranged from 70°F to 64.4°F, with 66°F being typical.

The test procedure using the recovery test was to start with a tank of 55°F water and heat it up until 135°F or the maximum thermostat cutout temperature was attained. The test procedure followed paragraphs 2.2 through 2.9 in that order. The test procedures, test conditions and instrumentation requirements were as specified in reference [2] . The standby loss test was conducted as specified by reference [2] and verified by the cool-down technique as shown in figure 2.

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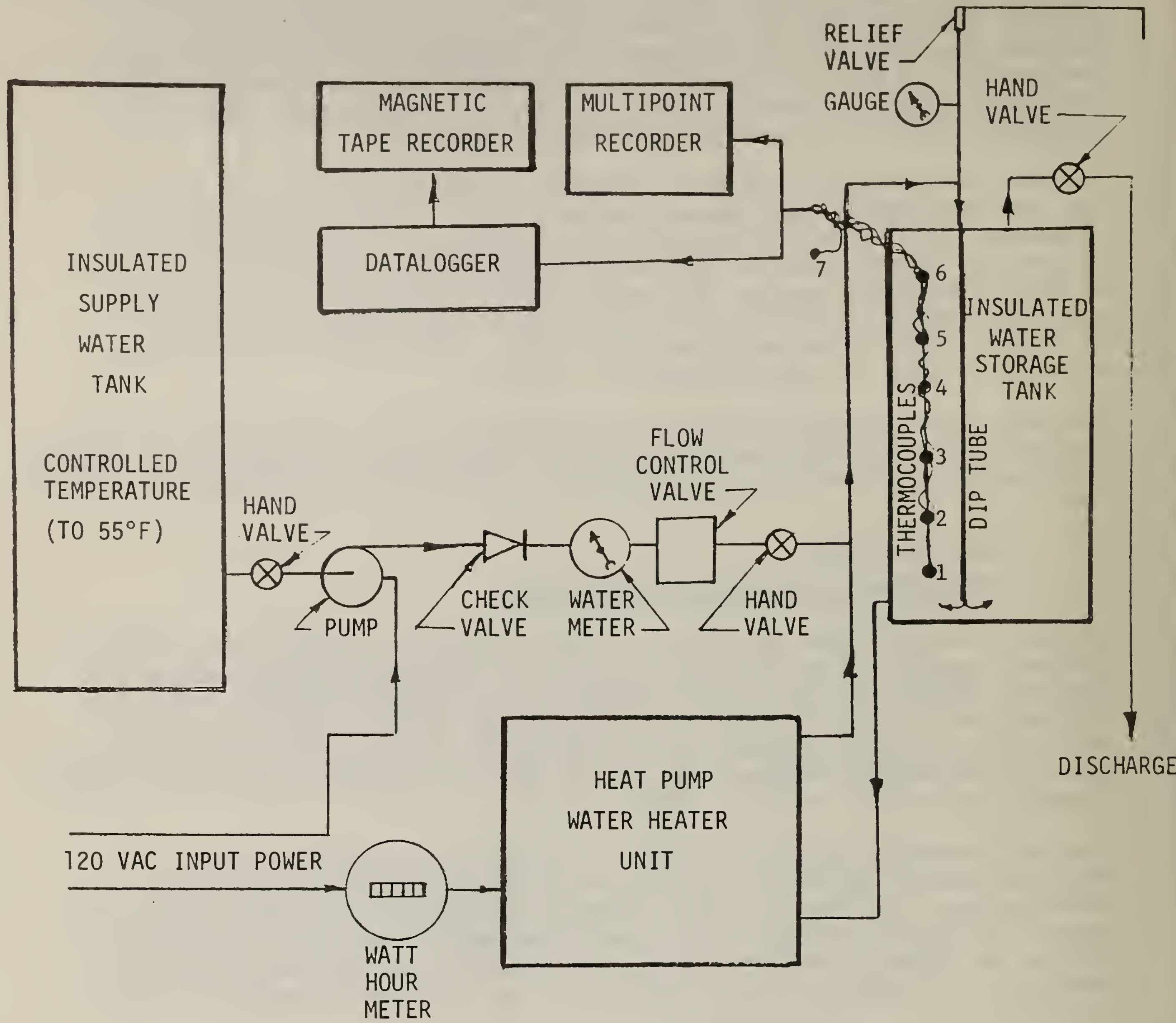
* Note: Numbers in brackets refer to references at the end of this report.

** Note: Inch-pound units are used in this report to be consistent with DOE and other published test procedures for other water heater types. A conversion table is included in the Appendix (Table 3).

*** Energy factor is the ratio of the daily hot water energy consumption to the average daily energy consumption of a particular water heater and it differs from the recovery efficiency because of the inclusion of the effects of the system standby losses.

**** The value of 64.3 gallons per day is currently specified in the DOE test procedure for water heaters as representative of the typical daily household hot water usage.



HEAT PUMP WATER HEATER HOT WATER DRAW SCHEDULE TEST SETUP

FIGURE 1.

All equations are defined in paragraph 2.2 to 2.12 and all symbols used are defined on pages v and vi.

2.2 INPUT POWER DETERMINATION

The input power, P, was determined using equation (1) where the total energy was measured for the heat up of a tank of cold (55°F) water to the maximum temperature (thermostat cut-out temperature). The duration of the test was measured in hours. The average power, in kilowatts, is the energy used, in kilowatt hours, divided by the time in hours.

input power determination, expressed in kilowatts and defined as:

$$P = \frac{Z}{Tr} \tag{1}$$

where: Z = total electrical energy to the heat pump during test (kilowatt hours)

Tr = duration of the recovery test (hours).

2.3 RECOVERY EFFICIENCY DETERMINATION

The recovery efficiency, Er, was determined using equation (2) where the resultant was the average recovery efficiency during the test which was run in conjunction with the input power determination test in paragraph 2.2. It was necessary to measure the mean tank temperature at the commencement and termination of this test in order to determine the mean water temperature rise, ΔT1.

Recovery efficiency, dimensionless and defined as:

$$Er = \frac{(k)(V)(\Delta T1)}{(Z)(3412\ \text{Btu/kWh})} \tag{2}$$

where: k = specific heat of water (8.25 Btu/(gallon - °F))
V = tank capacity (gallons)
ΔT1 = difference between the initial mean tank temperature and the final mean tank temperature during recovery test,

$(T_f - T_i)$, (°F)

Z = as defined in 2.2

2.3.1 RECOVERY EFFICIENCY DURING THE DIFFERENTIAL TEMPERATURE RISE

The recovery efficiency during the differential temperature (the temperature difference from the thermostat cut-in to cut-out) rise, Erd, was determined using equation (3). The value for Erd will differ from that for Er since recovery efficiency as a function of tank water temperature is not linear. The value for Erd is needed in equation (4) in order to compute the standby energy loss of the water tank and HPWH system. To determine the value for Erd, one must know the difference in mean tank water temperature at the thermostat cut-in from the thermostat cut-out and the energy consumed by the HPWH to effect this water temperature rise.

Recovery efficiency during the differential temperature rise, dimensionless and defined as:

$$Erd = \frac{(k)(V)(\Delta T6)}{(Z)(3412\ Btu/kWh)} \qquad (3)$$

where: $\Delta T6$ = difference between the mean high and mean low tank water temperature with thermostat differential, $\left(T_{max,\ cut\ out} - T_{min,\ cut\ in}\right)$, (°F), k, V and Z are defined above

2.4 STANDBY LOSS DETERMINATION

The standby loss, S, was determined by test using the test procedure described in reference [2] and equation (4). The second term in the numerator accounts for the energy related to any difference between the mean tank temperature at the start of a test and that at the end of a test. The standby loss is expressed as a decimal loss per hour and is subsequently used in equation (6) to determine the average hourly hot water storage energy consumption.

Standby loss is the ratio of the amount of energy lost per hour to the available energy above the datum of the average ambient air temperature and defined as:

$$S = \frac{(Z)(3412\ Btu/kWh) - \frac{(k)(V)(\Delta T3)}{Erd}}{(k)(V)(\Delta T2)(Ts)} \qquad (4)$$

where: $\Delta T3$ = difference between the initial and final mean tank temperature from the start to the end of a standby loss test, $(T_f - T_i)$, (°F)

$\Delta T2$ = difference between the average value of the mean tank temperature and the average value of the ambient air temperature during the standby loss test, (°F)

Z, k and V are defined above

2.5 DAILY WATER HEATING ENERGY CONSUMPTION

The daily water heating energy consumption, Cwh, was determined by using equation (5) which requires the recovery efficiency, Er, as determined in section 2.3. The daily water heating energy consumption, Cwh, is then used in equation (7) to determine the average daily water heater energy consumption.

Daily water heating energy consumption, expressed in Btu per day and defined as:

$$Cwh = \frac{(k)(U)(\Delta T4)}{Er} \qquad (5)$$

Where: $\Delta T4$ = the nominal difference between the initial mean tank temperature and the final mean tank temperature, (90°F; fixed by reference [2])

U = the nominal daily hot water usage, (64.3 gallons)

k = is defined in 2.3

2.6 AVERAGE HOURLY HOT WATER STORAGE ENERGY CONSUMPTION CALCULATION

The average hourly hot water storage energy consumption, Cus, was calculated using equation (6) with the standby loss, S, determined from the preceding section 2.4. The value calculated is subsequently used in equation (7) to calculate the average daily water heater energy consumption.

Average hourly hot water storage energy consumption, expressed in Btu per hour and defined as:

$$Cus = \frac{(S)(k)(V)(\Delta T5)}{Erd} \tag{6}$$

where: $\Delta T5$ = the difference between the nominal mean tank temperature and the nominal mean ambient air temperature (60°F; fixed by reference [2])

Z, k and V are defined above

2.7 AVERAGE DAILY ENERGY CONSUMPTION

The average daily energy consumption Cy was calculated from equation (7). The values of Cwh (from section 2.5), Cus (from section 2.7) and P (from section 2.2) are used to make the necessary calculations. Equation (7) is the same as the equation in section 4.5.4 of reference 2 except that the terms for heat trap credits (Jh and Jc) are missing since there were no heat traps used in these tests.

Average daily energy consumption (without heat traps), expressed in kilowatt hours per day and defined as:

$$CY = \left(\frac{1}{3412\ \text{Btu/kWh}}\right)\left[Cwh + (Cus)\left(\frac{24\ \text{hrs}}{\text{day}} - \frac{Cwh}{(P)(3412\ \text{Btu/kWh})}\right)\right] \tag{7}$$

where: Cwh is defined in 2.5

Cus is defined in 2.6

P is defined in 2.2

2.8 DAILY HOT WATER ENERGY CONSUMPTION CALCULATION

The daily hot water energy consumption, Cc, was calculated from equation (9) using the values prescribed in reference [2].

Daily hot water energy consumption, expressed in Btu per day and defined as:

$$Cc = (k)(U)(\Delta T4) \tag{8}$$

where: $\Delta T4$ and U are defined in 2.5

k is defined in 2.3

2.9 ENERGY FACTOR CALCULATION

The energy factor, EF, was calculated from equation (9) using the values of Cc (from section 2.8) and Cy (from section 2.8).

Energy factor derived from cold tank recovery test, dimensionless and defined as:

$$EF = \frac{Cc}{(Cy)(3412\ Btu/kWh)} \tag{9}$$

where: Cc and Cy are defined above

2.10 RECOVERY RATE DETERMINATION

The recovery rate, R, in gallons per hour was determined by equation (10). The average power, P, (from section 2.2) and Erd (from section 2.3.1 are used to calculate the recovery rate in gallons per hour. This is a performance measure of a water heater's ability to supply hot water. It is not used in the energy determination of a HPWH.

Recovery rate, expressed in gallons per hour and defined as:

$$R = \frac{(P)(Erd)(3412\ Btu/kWh)}{(k)(\Delta T4)} \tag{10}$$

where: P is defined in 2.2

Erd is defined in 2.3.1

k is defined in 2.3

2.11 COLD TANK START-UP RECOVERY TEST

The procedures from sections 2.2 and 2.9 were used to determine the energy factor of a HPWH based upon a cold tank start-up (recovery test). Since the recovery efficiency of a HPWH varies as a function of the water temperature and since a water heater is normally full (or nearly full) of hot water, any test based upon a cold tank start-up may not give the same results as an actual installed water heater. An alternative test method was devised to simulate installed conditions and this method is described in section 2.12.

2.12 ENERGY FACTOR DERIVED FROM A SIMULATED USE TEST

This test is a 24-hour test, starting with a full tank of hot water. The mean tank temperature is determined at the start of the test in addition to the time of the commencement of the test. Water is drawn out in a schedule pattern of equal draws to total 64.3 gallons per day. The draw part of the test can be made during the normal work day so that during the off-hours time of the test the HPWH is in a standby mode. Various draw schedule tests were run with 2, 3, 4 and more draws since by previous tests, ref [5], it was determined that there were no significant differences between such draw schedule test results and variable draws as may be actually encountered in "typical use patterns." The draw schedule used for most of the tests consisted of four equal draws, totaling 64.3 gallons of hot water per day. The time for the draws and subsequent recovery was about six hours.

These simulated usage tests are all of 24 hours duration. At the end of 24 hours, the mean temperature must be determined and the time of the test termination recorded.

The energy factor based upon simulated use, EFsu, is calculated using equation (11) where Cc is determined in section 2.10 and Erd is determined from section 2.3.

Energy factor, derived from a 24-hour test with a hot tank and simulated day's use of 64.3 gallons of hot water, dimensionless and defined as:

$$EFsu = \frac{Cc}{(Z)(3412\ \text{Btu/kWh}) - \frac{(k)(V)(\Delta T3)}{Erd}} \tag{11}$$

where: Cc is defined in 2.8

Z is defined in 2.2

k and V are defined in 2.3

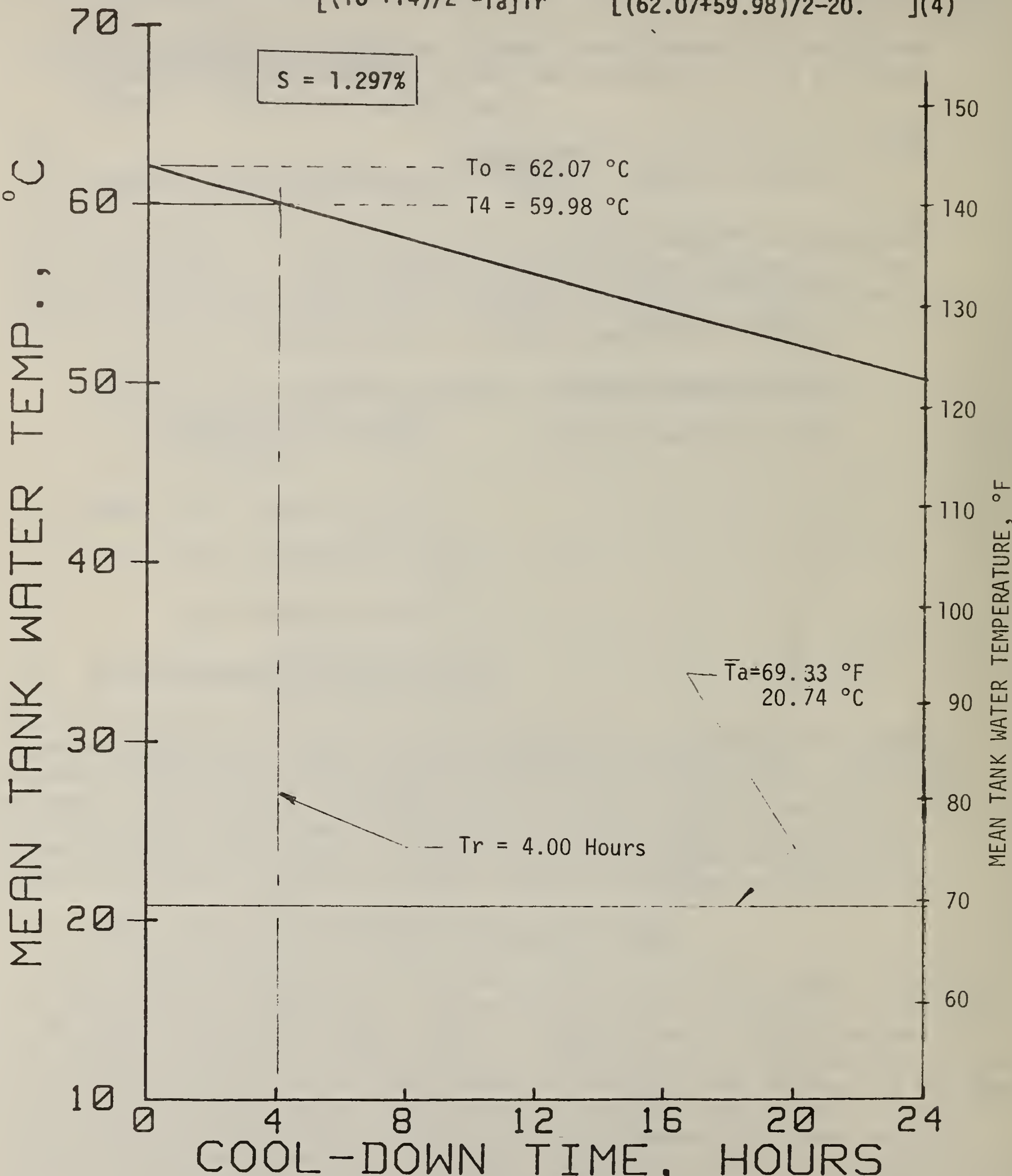
ΔT3 is defined in 2.4

Erd is defined in 2.3.1

Standby Loss By Cool-down of Tank:

Given:	To=Temp @ Time = 0 Hours	To=62.07 °C
	T4=Temp @ Time = 4 Hours	T4=59.98 °C
	$\overline{T}a$=Temp, Ambient (Avg.)	$\overline{T}a$=20.74 °C

$$S = \frac{(To - T4)(100)}{[(To + T4)/2 - \overline{T}a]Tr} = \frac{(62.07-59.98)(100)}{[(62.07+59.98)/2-20. \quad](4)}$$



STANDBY LOSS BY COOL-DOWN OF TANK

FIGURE 2.

3. RESULTS

3.1 COLD TANK RECOVERY TEST

The results of cold tank recovery tests are shown in the upper portion of Table 1. The program to make the computations and some sample computations are included in Appendix B.

The energy factor, EF, computed from equation (10) for unit A is 1.719, while the value for unit B is 1.703. The mean of these two values is 1.711. This test method is different from the normal usage pattern of water heaters in actual use and since there is no draw of hot water, it may result in values that are not representative of actual service conditions.

Table 1

Summary of test results

Cold Tank Recovery Tests								
UNIT	EF	P(KW)	Cwh (Btu)	ΔT1 (°F)	Cy (kWh)	Ta (°F)	EF	Standard Deviation
"A"*	2.210	1.296	21,602	85.6	8.159	66.9	1.719	0.0100
"B"**	2.179	1.225	21,920	80.7	8.218	67.0	1.703	0.0255
						MEAN	1.711	

SIMULATED USE TESTS, TWENTY-FOUR HOURS WITH DRAWS TOTALING 64.3 GALLONS							
UNIT	Z (kWh)	Tf (°F)	Ti (°F)	Cy (kWh)	Ta (°F)	EFsu	Standard Deviation
"A"#	11.256	132.964	136.477	10.557	69.3	1.421	0.0860
"B"##	8,483	132.188	134.276	8.668	69.6	1.614	0.1441
					MEAN	1.518	

* These data are the mean of 6 tests, see table 2 for detailed data for each test.

** These data are the mean of 9 tests, see table 2 for detailed data for each test.

\# These data are the mean of 3 tests, see table 2 for detailed data for each test.

\## These data are the mean of 6 tests, see table 2 for detailed data for each test.

3.2 SIMULATED USE TESTS

The results of simulated use tests are shown in the lower portion of table 1.

The energy factor, EF_{su}, derived from simulated day's use of 64.3 gallons of hot water by a draw test and standby portion to simulate the HPWH installed in a home for unit A was 1.421 while the value for unit B was 1.614. The mean of these two values is 1.518.

3.3 DISCUSSION OF TEST RESULTS

These two units, A and B, showed very similar test results when the cold water recovery test was used as the basis for energy factor determination. When these two units were tested with a simulated use test method, the energy factor of unit A was 88.7 percent of the value of unit B.

The mean value of the energy factors of units A and B is 1.711 when a cold tank recovery test is used; the mean value of the energy factors of these same units is 1.518 when the simulated use test method is used. The former energy factor (1.711) is 112.7 percent of the latter result (1.518).

It is difficult to accurately simulate actual home use conditions in the laboratory; however the simulated use test is more nearly representative of actual conditions than the cold tank recovery test. Earlier testing (ref. 5) has shown that the variations in draw schedules do not have a significant effect upon the energy factor when the same daily gallons of hot water are used with an integral type HPWH. It is suspected that this is a general phenomenon with water heaters since reference [6] also found only small variations in the energy factor with various draw schedules with a solar water heater.

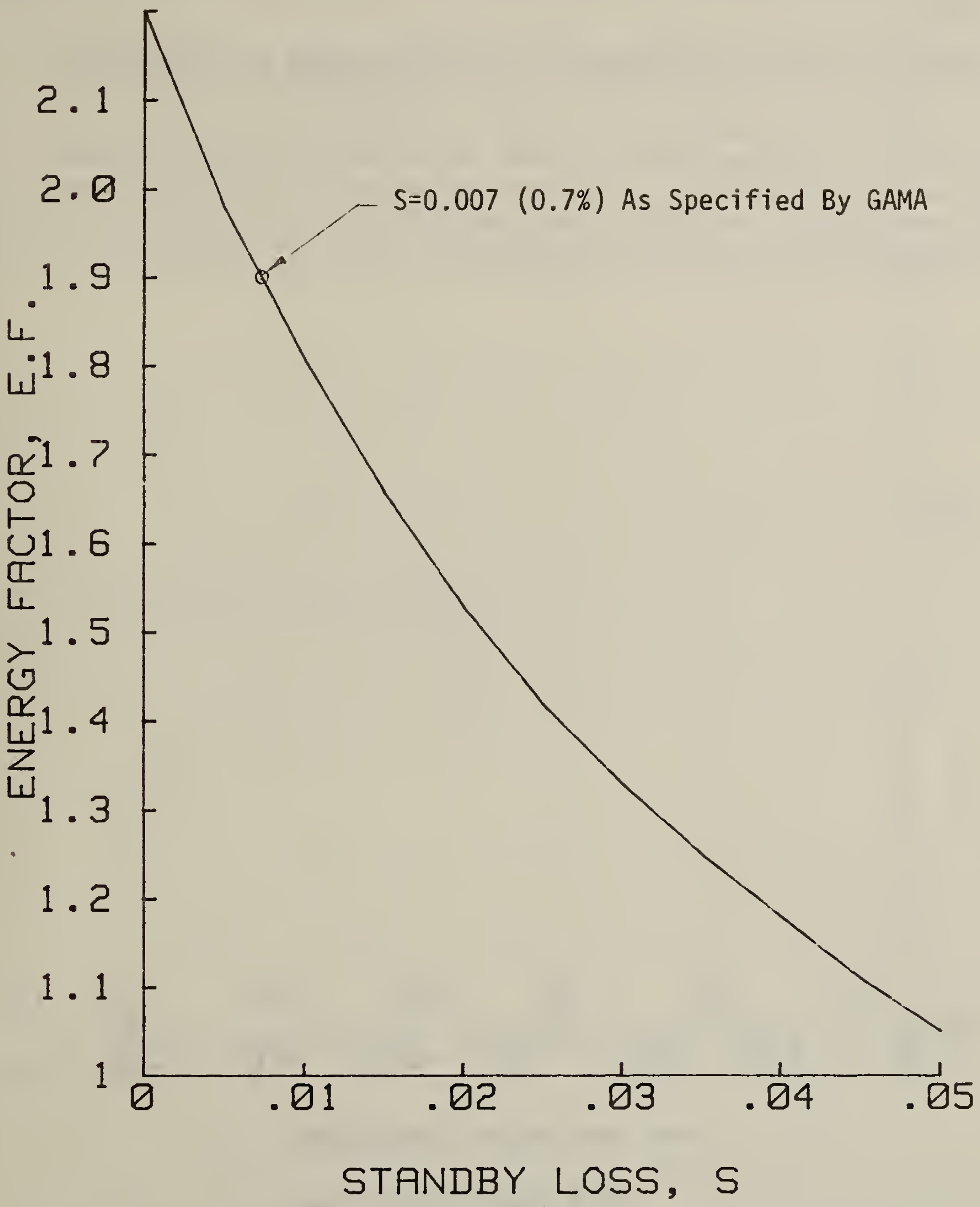
3.4 THE VARIATION OF ENERGY FACTOR WITH CHANGES IN STANDBY LOSS

Figure 3 shows that the energy factor (EF) derived from a cold tank recovery test is significantly affected by the standby loss(es) of the system. This curve is developed by holding the values of Er, Cwh, P, k, U, $\Delta T4$, and V constant and allowing S to vary from 0.0 to 0.05 per hour. This results in the variation of energy factor from 2.196 to 1.054 as shown. Equations (5), (6), (7), and (10) are used to develop this curve. The proposed GAMA test procedure, ref [1], specified that S = 0.7 percent per hour. Figure 3 shows this point relative to S from 0 to 5 percent loss per hour. A consequence is that with an identical unit under test, the energy factors would vary from 1.98 to 1.05 when the standby loss varied from 0.5 percent per hour to 5.0 percent per hour.

The specified value of S = 0.7 percent per hour is probably lower than that of water heater tanks that might be used with these add-on type HPWH's. By comparison, a "high efficiency" electric water heater with foam insulation has a loss of about 1.0 percent per hour; the tank used for these tests had a standby loss of 1.3 percent per hour.

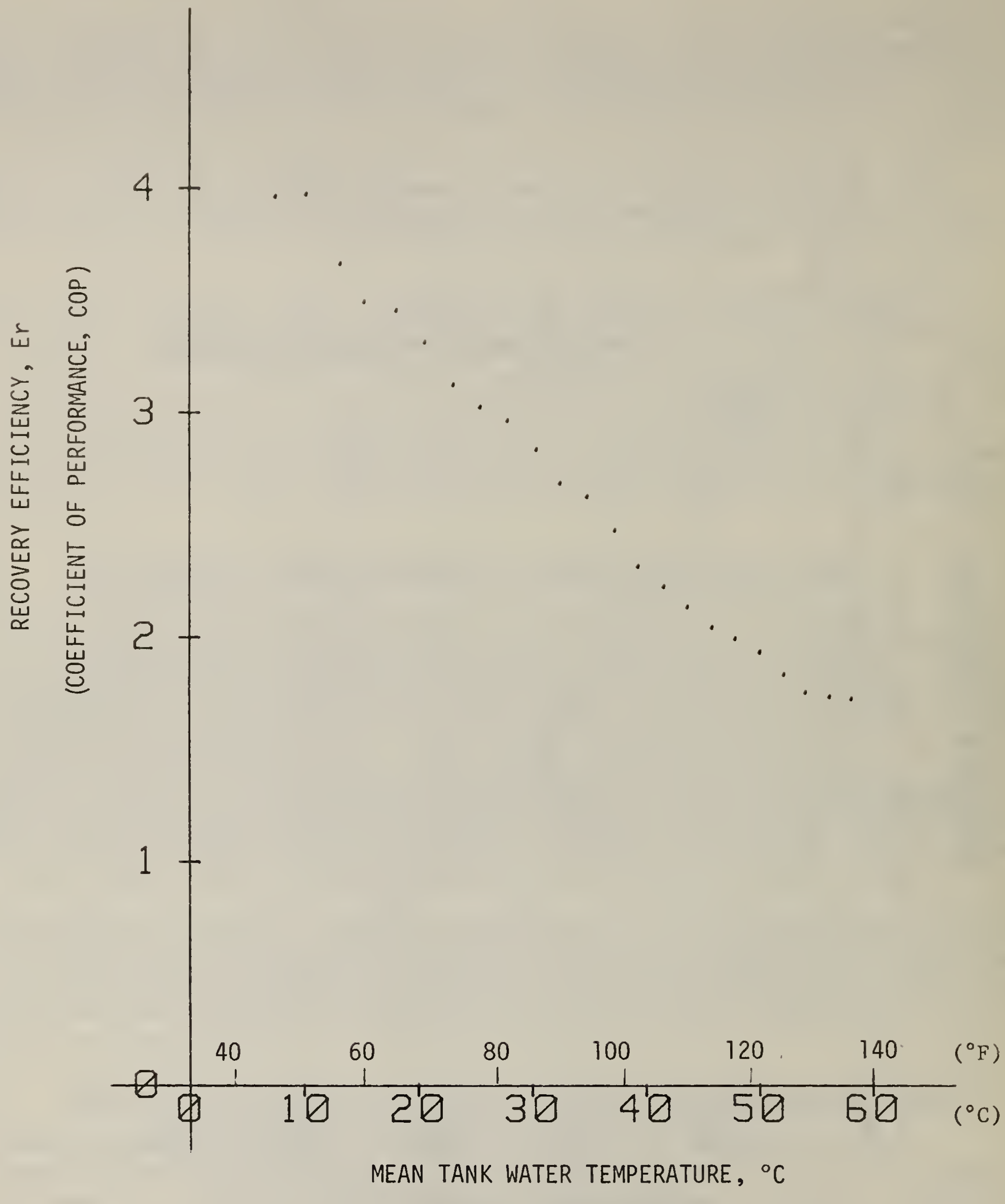
3.5 ANALYSIS TO DETERMINE AN ALTERNATIVE STARTING MEAN TANK TEMPERATURE

An analysis to compensate for the differences in test results by using a different starting water temperature for the recovery test method is included in Appendix A. This analysis showed that if the mean energy factor determined by a 24-hour simulated use test is used to compute the average daily water heater energy consumption (Cy) then this value can be used to compute the daily water heating energy consumption (Cwh), using an assumed standby loss of 1.3 percent per hour and an assumed power of 1.21 kilowatts. This is used to



ENERGY FACTOR AS A FUNCTION OF STANDBY LOSS
(WITH POWER ASSUMED @ 1.21 kW; Cus=25,096(S); Cwh=31,739)

FIGURE 3.



(FOR A HPWH, WITHOUT TANK)

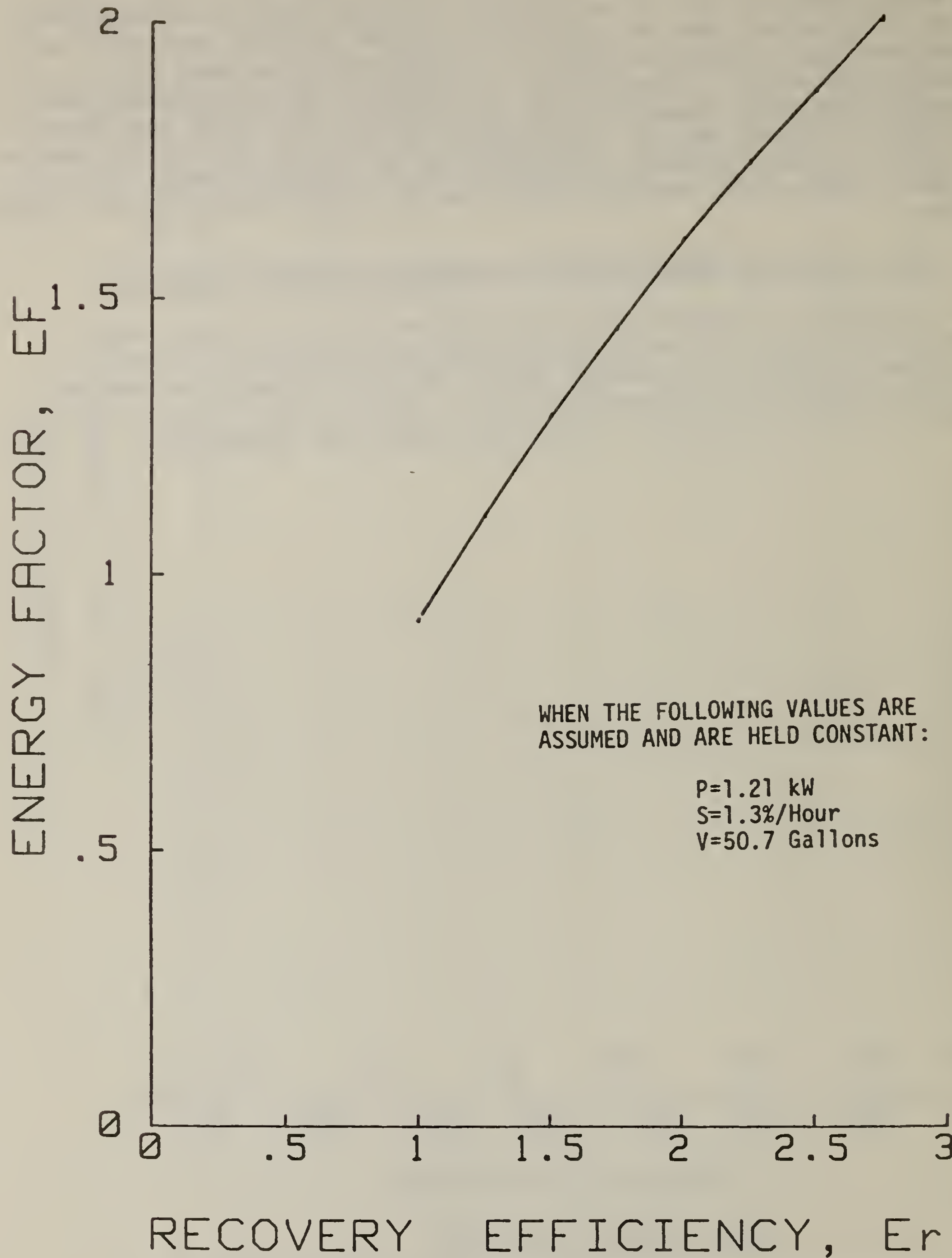
RECOVERY EFFICIENCY AS A FUNCTION OF MEAN TANK WATER TEMPERATURE

FIGURE 4.

compute the average hourly hot water storage energy consumption (Cus). When Cus is known, then the value of the recovery efficiency (Er) can be calculated. After Er is determined, then the equivalent mean tank starting temperature can be calculated when the characteristics of the HPWH system are known by an empirical determination. In the example in Appendix A, it was determined that the starting tank water temperature should be 114.3°F to give the same energy factor using a recovery test vs. the simulated use test. A recovery test was run with a 114°F starting tank water temperature and the resultant energy factor was 1.510 which compares well with mean energy factor of 1.518 obtained by the simulated use tests.

3.6 THE VARIATION OF ENERGY FACTOR WITH CHANGES IN RECOVERY EFFICIENCY

Figure 5 shows that the energy factor (EF) derived from a cold tank recovery test is significantly affected by the recovery efficiency (Er). This curve is developed by holding the values of Cwh, P, k, S, U, $\Delta T4$ and V constant and allowing the values of Er to vary from 1 to 3. Figures 4 and 6 show the variation of recovery efficiency (Er) with variable mean tank water temperature.



ENERGY FACTOR AS A FUNCTION OF RECOVERY EFFICIENCY

FIGURE 5.

4. CONCLUSIONS

It is concluded that the recovery test from a cold tank start-up results in a higher energy factor value than from a simulated use test with a standby time and draws of hot water totaling 64.3 gallons per day.

When an analysis was made to find starting mean tank water temperature to compensate for this difference and use a recovery test to determine the energy factor, it was found that the starting temperature should be about 114°F. This higher starting mean tank temperature was used for a recovery test and the resultant energy factor compared well with the simulated use test results.

There is a problem using the current DoE water heater test procedure to test a HPWH in that it gives a higher energy factor than that of a simulated use test procedure. This is because the performance of a HPWH is affected by the mean tank water temperature (see figure 4).

The specification of a hot water storage tank's standby loss has a significant effect on the resulting energy factor. Since there is a wide range of standby losses of water heater storage tanks, this matter requires more investigation to see if these effects can be reduced.

There is a need to have a uniform test method that is agreed to by manufacturers, associations and consumers that will result in accurate information on the cost of operation of HPWH's. There are many variables that affect the overall system efficiency (energy factor). Many of the variables are a compromise so that the operating costs of heating water for an "average household" is also a compromise. Consumers need information that is current, creditable and reasonable to enable them to make water heater purchasing decisions that are based upon tests that are representative of actual installed operating conditions.

5. RECOMMENDATIONS

5.1 STORAGE TANK STANDBY LOSS AND TANK WATER STARTING TEMPERATURE

It has been determined that it is possible to use a recovery test with a starting tank water temperature different from 55° to yield an equivalent energy factor to that of a draw test of 64.3 gallons with a 55°F supply water temperature. Tests in this report indicate that the required intermediate temperature should be about 114.°F; however, since these tests were rather limited, more information is needed to determine:

1. For HPWH's in general, what is the appropriate starting water temperature for use in a recovery test in order to yield the same energy factor as that obtained in a 24-hour simulated use test with a 64.3 gallon draw schedule and a supply water temperature of 55°F.

2. Since it is probable that most add-on type HPWH's will be used with conventional electric water heater storage tanks and because the standby loss of the tank is an important variable in the energy factor determination, any specified value of standby loss must be carefully determined. Reference [7] states "A value of 2%/h for cooldown loss is typical of EWH [Electric Water Heaters] with fiberglass insulation." (page 18, paragraph 4.5). Tests at NBS indicate that high efficiency foam type of EWHs have standby losses of 1% per hour. Until such time as a more accurate determination of average standby loss is made it is recommended that the value of 1.5% per hour should be used.

5.2 DETERMINATION OF ENERGY FACTOR, EFSu

It is recommended that the test to determine the energy factor (EFSu) should be by a simulated use test of 24 hours duration with four equal draws (totaling 64.3 gallons of hot water per day) and that such a determination be made using equation (11) of this report. It should be noted that normally these four draws can be made within a period of six hours or less, which means that this recommended test can be run during normal working hours. It is also recommended that the first draw be started after the thermostat cut-out; that the second draw be commenced after the thermostat cut-out after the first draw recovery is complete; that the third draw be started after the thermostat cut-out after the second draw recovery is completed; that the fourth and final draw be started after the thermostat cut-out after the third draw recovery is completed and that the final draw be trimmed so that the total of all draws is 64.3 gallons. The mean tank temperature at the beginning and end of the 24-hour test should be determined and the energy (in kWh) be measured during this test. The supply water should be at 55°F.

5.3 DETERMINATION OF RECOVERY RATE

It is recommended that the recovery rate (R) in gallons per hour be determined by use of equ (8) except that the value of Erd should be used in place of Er so that:

$$R = \frac{(P)(Erd)(3412\ \text{Btu/kWh})}{(8.25\ \text{Btu/gal °F})(90\text{°F})}$$

or simplified:

$$R = (4.595)(P)(Erd)(\text{gal/hour})$$

6. REFERENCES

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[6] Fisher, Ronald A., Jr. and Fanney, A. Hunter, "Thermal Performance Comparison for a Solar Hot Water System Subjected to Various Hot Water Load Profiles," to be published in the ASHRAE Journal.

[7] Wan, C. Andrew, Palla, Robert L., Jr., and Harris, James E., "Development of an Energy Test Method for a Dedicated Water-Heating Heat Pump," NBSIR 81-2372, National Bureau of Standards, Washington, D.C., November 1981.

This is an analysis to determine the starting mean tank water temperature that would result in the same energy factor by use of the cold tank recovery test as would be obtained by the 24-hour simulated test (with standby time and a draw schedule with a 55°F supply water temperature to simulate usage.

From the simulated use test, the mean value of EFsu was found to be 1.518.

Rearrange equation (10) and solve for Cy:

$$Cy = \frac{Cc}{(EFsu)(3412\ Btu/kWh)}$$

and substituting from equation 9 for Cc and inserting known values:

$$Cy = \frac{8.25\ Btu/gal\ °F)(64.3\ gal/day)(90°F)}{(1.518)(3412\ Btu/kWh)}$$

$$Cy = 9.218\ kWh/day.$$

Use eq. (6) and assume: standby loss in 1.3 percent per hour, temperature difference (ΔT5) is 60°F, the tank capacity (V) is 50 gallons, and the recovery efficiency during the differential temperature rise (Erd) is 1.57, to determine the value of Cus:

$$Cus = \frac{(S)(k)(V)(\Delta T5)}{Erd}.$$ Insert known and assumed values:

$$Cus = \frac{(0.013/hour)(8.24\ Btu/gal\ °F)(50\ gal)(60°F)}{1.57}$$

(Note: The product of the terms of the numerator of this equation represents the tank cooldown loss and must be divided by Erd:1.57 to represent the electrical energy equivalent needed to replace this thermal loss).

$$Cus = 204.9\ Btu/hour$$

Insert this value and the assumed power of 1.21 kilowatts into equation (7) above:

$$Cy = \left(\frac{1}{(3412\ Btu/kWh)}\right)\left[Cwh + \left(204.9\ \frac{Btu}{hour}\right)\left(24\ \frac{hrs}{day} - \frac{Cwh}{(1.21\ kw)\left(3412\ \frac{Btu}{kWh}\right)}\right)\right]$$

Note: This is per 4.5.4 of ref [2] and Jh and Jc are zero since no heat traps were used.

Collect terms and simplify to:

$$Cy = \frac{1}{(3412 \text{ Btu/kWh})} (Cwh + 4918 - 0.04964 \text{ Cwh})$$

Substitute computed value (9.218 kWh/day) for Cy and, collect terms and solve for Cwh:

$$(9.218 \text{ kWh/day})(3412 \text{ Btu/kWh}) - 4918 \text{ Btu} = Cwh - 0.04964 \text{ Cwh}$$

$$0.9504 \text{ Cwh} = 26{,}534 \text{ Btu/day}$$

$$Cwh = \frac{26{,}534 \text{ Btu/day}}{0.9504}$$

$$Cwh = 27{,}920 \text{ Btu/day}$$

Now use this value with equation (5) and rearrange to solve for Er:

$$Cwh = \frac{(k)(U)(\Delta T4)}{Er}$$

$$Er = \frac{(k)(U)(\Delta T4)}{Cwh}$$ and substitute known or computed values:

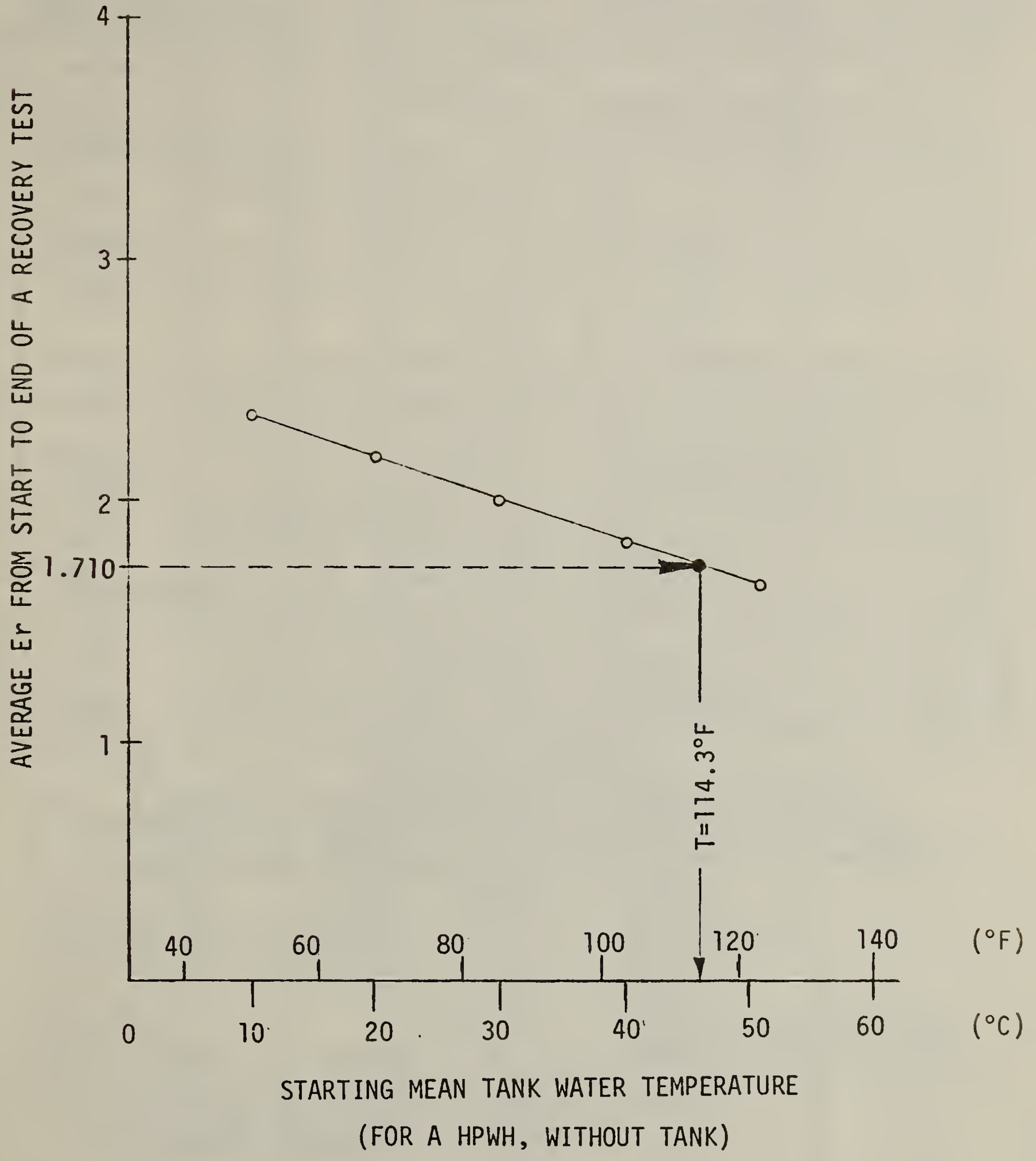
$$Er = \frac{(8.25 \text{ Btu/gal °F})(64.3 \text{ gal/day } (90°F)}{27{,}920 \text{ Btu/day}}$$

$$Er = 1.710$$

Now use the characteristics of the HPWH tested and shown by the solid line in figure 6. This HPWH has been determined by test to exhibit the characteristics to enable a graphical solution for a starting tank water temperature of:

$$T = 114.3°F$$

This starting water temperature would apply only to the particular HPWH tested under the specified conditions. It would not necessarily apply to all HPWH's. Each HPWH type would require the duplicate testing of a recovery test and a draw schedule test as cited in this analysis to ensure the suitability of a different starting water temperature to simulate a daily usage of 64.3 gallons of hot water heated from a 55°F supply. However, after this draw test was done, all future testing of identical models (e.g. for quality control test) could be done using a recovery test without any draw and use the specific starting water temperature found for that model.



RECOVERY EFFICIENCY AS A FUNCTION OF STARTING MEAN TANK WATER TEMPERATURE
(FOR A RECOVERY TEST)

FIGURE 6.

TABLE 2

Detailed Test Results

COLD TANK RECOVERY TESTS										
Unit	Z(kWh)	Tr(hrs)	Tf(°F)	Ti(°F)	Er	Cwh(Btu)	P(kw)	ΔTI(°F)	Cy(kWh/day)	EF
A	4.734	3.688	140.27	54.00	2.234	21,370	1.284	86.27	8.092	1.729
A	4.731	3.673	140.63	55.00	2.219	21,518	1.288	85.63	8.133	1.720
A	4.703	3.553	140.09	55.94	2.193	21,766	1.331	84.15	8.216	1.703
A	4.779	3.696	140.31	54.19	2.209	21,614	1.293	86.12	8.161	1.715
A	4.789	3.720	140.49	55.00	2.189	21,810	1.287	85.49	8.212	1.704
A	4.752	3.669	140.68	54.73	2.217	21,532	1.295	85.95	8.140	1.719
B	4.771	3.660	134.02	52.74	2.089	22,858	1.304	81.28	8.503	1.646
B	4.542	3.713	135.99	55.34	2.177	21,933	1.223	80.65	8.221	1.702
B	4.475	3.653	136.25	56.72	2.179	21,914	1.225	79.53	8.216	1.703
B	4.581	3.800	135.86	55.55	2.149	22,215	1.206	80.31	8.289	1.688
B	4.585	3.758	135.47	51.80	2.237	21,342	1.220	83.67	8.060	1.736
B	4.420	3.667	134.66	55.04	2.208	21,620	1.205	79.62	8.129	1.721
B	4.420	3.619	135.71	56.03	2.210	21,604	1.221	79.68	8.131	1.721
B	4.550	3.767	135.83	54.71	2.182	21,883	1.210	81.12	8.202	1.706
B	4.545	3.751	135.92	55.13	2.179	21,910	1.212	80.79	8.210	1.704

SIMULATED USE TESTS, TWENTY-FOUR HOURS WITH DRAWS TOTALING 64.3 GALLONS				
Unit	Z(kWh)	Tf(°F)	Ti(°F)	EFsu
A	9.024	139.68	140.68	1.535
A	9.168	131.85	139.68	1.415
A	11.106	131.75	130.49	1.273
B	7.851	127.40	135.09	1.635
B	8.811	134.87	135.95	1.570
B	10.166	134.99	129.98	1.442
B	7.623	133.82	135.92	1.790
B	7.699	131.93	133.82	1.777
B	10.267	137.24	127.40	1.494

Table 3 Units Conversion Table: SI/INCH-POUND/SI

To Convert	Multiply By	To Obtain
gpm (Gallons/minute)	0.06309	L/s (Liters/second)
L/s (Liters/second)	15.85	gpm (Gallons/minute)
g (Gallons)	3.785	L (Liters)
L (Liters)	0.2642	g (Gallons)
in (Inches)	2.54	cm (Centimeters)
cm (Centimeters)	0.3937	in (Inches)
ft (Feet)	0.3048	m (Meters)
m (Meters)	3.281	ft (Feet)
BTU (British Thermal Units)	1.055	kJ (kilojoules)
kJ (kilojoules)	0.9479	BTU (British Thermal Units)

<u>Temperature (T), Conversion Equations:</u>

For Temperature Use:

°F to °C: $[(T)°F - 32°F](5/9) = (T)°C$

°C to °F: $[(T)°C](9/5) + 32°F = (T)°F$

<u>For Temperature Differentials or Tolerances Use:</u>

°F to °C: $(T)°F(5/9) = (T)°C$

°C to °F: $(T)°C(9/5) = (T)°F$

BASIC PROGRAM TO COMPUTE ENERGY EQUATIONS

(; denotes print command)

```
LIST
-10 REM THIS IS A BASIC PROGRAM TO COMPUTE ENERGY EQUATIONS
-20 REM   AND TO COMPUTE ENERGY FACTOR. NEEDED INPUTS ARE:
-30 REM  ENERGY (WATT-HOURS), MEAN TANK (FINAL) AND (INITIAL)
-40 REM  TEMPERATURES, WITH A 50.7 GALLON STORAGE TANK WITH
-45 REM  STANDBY LOSS OF 1.3% PER HOUR. ALL TEMPS., DEG. (C).
-50 ;"ENERGY USED DURING RECOVERY TEST (WATT-HOURS) ?"
-60 INPUT E1
-70 ;"DURATION OF RECOVERY TEST IN HOURS? "
-80 INPUT T9
-90 P=(E1/T9)/1000
-100 ;"FINAL MEAN TANK WATER TEMPERATURE, DEGREES C?"
-110 INPUT K
-120 ;"INITIAL MEAN TANK WATER TEMPERATURE, DEGREES C ?"
-130 INPUT L
-140 T1=K-L
-150 E2=(220.66)*(T1)/E1
-160 REM E2=ER=RECOVERY EFFICIENCY
-170 REM C1=CWH=DAILY ENERGY TO HEAT WATER
-180 C1=47743/E2
-190 ;"RECOVERY EFFICIENCY, ER=";E2
-200 ;"DAILY WATER HEATING ENERGY, BTU/DAY, CWH=";C1
-210 REM S=STANDBY LOSS AS A DECIMAL LOSS PER HOUR
-220 S=.13E-1
230 REM C4=CUS=HOURLY STANDBY LOSS, BTU/HOUR.
-240 REM C5=CUS(24-CWH/3412P)
-250 C4=(S)*(8.25*50.7*60)
-260 C5=(C4)*(24-C1/(3412*P))
-270 REM C6=CY= DAILY WATER HEATING ENERGY, KWH/DAY
-280 C6=(C1+C5)/(3412)
-290 REM E4=EF=ENERGY FACTOR
-300 E4=(13.993)/(C6)
-310 ;"ENERGY USED IN RECOVERY TEST (WATT-HOURS) :";E1
-320 ;"AVERAGE POWER DURING RECOVERY TEST (KW):";P
-330 ;"DURATION OF RECOVERY TEST, HOURS :";T9
-340 ;"WATER TEMPERATURE RISE DURING THE RECOVERY TEST, C DEG.:";T1
-350 ;"FINAL MEAN TANK TEMPERATURE , DEG. C, DURING RECOVERY TEST:";K
-360 ;"INITIAL MEAN TANK TEMP., DEG.C, DURING RECOVERY TEST:";L
-370 ;"HOURLY STANDBY LOSS, BTU/HOUR = CUS :";C4
-380 ;"DAILY STANDBY LOSS, BTU/DAY :";C5
-390 ;"DAILY WATER HEATER ENERGY, KWH = CY :";C6
400 ;"ENERGY FACTOR = EF :";E4
-410 END
-BASICII
->
```

SAMPLE CALCULATIONS, UNIT "A"

```
  RUN
-ENERGY USED DURING RECOVERY TEST (WATT-HOURS) ?
->4779
-DURATION OF RECOVERY TEST IN HOURS?
->3.696
-FINAL MEAN TANK WATER TEMPERATURE, DEGREES C?
->60.17




-INITIAL MEAN TANK WATER TEMPERATURE, DEGREES C ?
->12.33
-RECOVERY EFFICIENCY, ER= 2.2089086
-DAILY WATER HEATING ENERGY, BTU/DAY, CWH= 21613.841
-ENERGY USED IN RECOVERY TEST (WATT-HOURS) : 4779
-AVERAGE POWER DURING RECOVERY TEST (KW): 1.2930195
-DURATION OF RECOVERY TEST, HOURS : 3.696
-WATER TEMPERATURE RISE DURING THE RECOVERY TEST, C DEG.: 47.84
-FINAL MEAN TANK TEMPERATURE , DEG. C, DURING RECOVERY TEST: 60.17
-INITIAL MEAN TANK TEMP., DEG.C, DURING RECOVERY TEST: 12.33
-HOURLY STANDBY LOSS, BTU/HOUR = CUS : 326.2545
-DAILY STANDBY LOSS, BTU/DAY : 6231.7489
-DAILY WATER HEATER ENERGY, KWH = CY : 8.1610755
-ENERGY FACTOR = EF : 1.7146024
-BASICII
->

  RUN
-ENERGY USED DURING RECOVERY TEST (WATT-HOURS) ?
->4787
-DURATION OF RECOVERY TEST IN HOURS?
->3.720
-FINAL MEAN TANK WATER TEMPERATURE, DEGREES C?
->60.27
-INITIAL MEAN TANK WATER TEMPERATURE, DEGREES C ?
->12.78
-RECOVERY EFFICIENCY, ER= 2.1890836
-DAILY WATER HEATING ENERGY, BTU/DAY, CWH= 21809.582
-ENERGY USED IN RECOVERY TEST (WATT-HOURS) : 4787
-AVERAGE POWER DURING RECOVERY TEST (KW): 1.286828
-DURATION OF RECOVERY TEST, HOURS : 3.72
-WATER TEMPERATURE RISE DURING THE RECOVERY TEST, C DEG.: 47.49
-FINAL MEAN TANK TEMPERATURE , DEG. C, DURING RECOVERY TEST: 60.27
-INITIAL MEAN TANK TEMP., DEG.C, DURING RECOVERY TEST: 12.78
-HOURLY STANDBY LOSS, BTU/HOUR = CUS : 326.2545
-DAILY STANDBY LOSS, BTU/DAY : 6209.5135
-DAILY WATER HEATER ENERGY, KWH = CY : 8.2119273
-ENERGY FACTOR = EF : 1.7039849
-BASICII
->
```

SAMPLE CALCULATIONS, UNIT "B"

```
-BASICII
->

  RUN
-ENERGY USED DURING RECOVERY TEST (WATT-HOURS) ?
->4558
-DURATION OF RECOVERY TEST IN HOURS?
->3.767
-FINAL MEAN TANK WATER TEMPERATURE, DEGREES C?
->57.683
-INITIAL MEAN TANK WATER TEMPERATURE, DEGREES C ?
->12.617
-RECOVERY EFFICIENCY, ER= 2.1817164
-DAILY WATER HEATING ENERGY, BTU/DAY, CWH= 21883.229
-ENERGY USED IN RECOVERY TEST (WATT-HOURS) : 4558
-AVERAGE POWER DURING RECOVERY TEST (KW): 1.2099814
-DURATION OF RECOVERY TEST, HOURS : 3.767
-WATER TEMPERATURE RISE DURING THE RECOVERY TEST, C DEG.: 45.066
-FINAL MEAN TANK TEMPERATURE , DEG. C, DURING RECOVERY TEST: 57.683
-INITIAL MEAN TANK TEMP., DEG.C, DURING RECOVERY TEST: 12.617
-HOURLY STANDBY LOSS, BTU/HOUR = CUS : 326.2545
-DAILY STANDBY LOSS, BTU/DAY : 6100.7688
-DAILY WATER HEATER ENERGY, KWH = CY : 8.2016405
-ENERGY FACTOR = EF : 1.7061221
-BASICII
->

  RUN
-ENERGY USED DURING RECOVERY TEST (WATT-HOURS) ?
->4545
-DURATION OF RECOVERY TEST IN HOURS?
->3.751
-FINAL MEAN TANK WATER TEMPERATURE, DEGREES C?
->57.733
-INITIAL MEAN TANK WATER TEMPERATURE, DEGREES C ?
->12.850
-RECOVERY EFFICIENCY, ER= 2.1790721
-DAILY WATER HEATING ENERGY, BTU/DAY, CWH= 21909.784
-ENERGY USED IN RECOVERY TEST (WATT-HOURS) : 4545
-AVERAGE POWER DURING RECOVERY TEST (KW): 1.2116769
-DURATION OF RECOVERY TEST, HOURS : 3.751
-WATER TEMPERATURE RISE DURING THE RECOVERY TEST, C DEG.: 44.883
-FINAL MEAN TANK TEMPERATURE , DEG. C, DURING RECOVERY TEST: 57.733
-INITIAL MEAN TANK TEMP., DEG.C, DURING RECOVERY TEST: 12.85
-HOURLY STANDBY LOSS, BTU/HOUR = CUS : 326.2545
-DAILY STANDBY LOSS, BTU/DAY : 6101.093
-DAILY WATER HEATER ENERGY, KWH = CY : 8.2095185
-ENERGY FACTOR = EF : 1.7044849
-BASICII
->
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5. AUTHOR(S)

James E. Harris

6. PERFORMING ORGANIZATION (If joint or other than NBS, see instructions)

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Washington, DC 20585

10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

Two different makes of add-on (without tank) heat pump water heaters (HPWH) were tested. Each of the HPWH's was subjected to a series of recovery tests similar to the Department of Energy (DOE) recovery test for conventional electric water heaters. The results of the tests (recovery efficiency, standby loss, input power, storage tank capacity and energy used) were used to compute an energy factor which could be used to calculate the estimated annual operating cost of such HPWH's. The energy factor was also determined by a series of simulated use tests consisting of four equal draws totaling 64.3 gallons of hot water per day. The average energy factor derived from the recovery tests was about 13 percent higher than that derived from the simulated use tests. Based upon the results of this limited test program it was recommended that a simulated use test be used to determine the energy factor for HPWH's without tank.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

Appliances; energy; heat pump water heaters; test procedures; testing; water heaters

13. AVAILABILITY

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